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Mitogen-Activated Protein Kinases Regulate Susceptibility to Ventilator-Induced Lung Injury

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Abstract

Background: Mechanical ventilation causes ventilator-induced lung injury in animals and humans. Mitogen-activated protein kinases have been implicated in ventilator-induced lung injury though their functional significance remains incomplete. We characterize the role of p38 mitogen-activated protein kinase/mitogen activated protein kinase-3 and c-Jun-NH2-terminal kinase-1 in ventilator-induced lung injury and investigate novel independent mechanisms contributing to lung injury during mechanical ventilation.

Methodology and Principle Findings: C57/BL6 wild-type mice and mice genetically deleted for mitogen-activated protein kinase kinase-3 (mkk3−/−) or c-Jun-NH2-terminal kinase-1 (jnk1−/−) were ventilated, and lung injury parameters were assessed. We demonstrate that mkk3−/− or jnk1−/− mice displayed significantly reduced inflammatory lung injury and apoptosis relative to wild-type mice. Since jnk1−/− mice were highly resistant to ventilator-induced lung injury, we performed comprehensive gene expression profiling of ventilated wild-type or jnk1−/− mice to identify novel candidate genes which may play critical roles in the pathogenesis of ventilator-induced lung injury. Microarray analysis revealed many novel genes differentially expressed by ventilation including matrix metalloproteinase-8 (MMP8) and GADD45α. Functional characterization of MMP8 revealed that mmp8−/− mice were sensitized to ventilator-induced lung injury with increased lung vascular permeability.

Conclusions: We demonstrate that mitogen-activated protein kinase pathways mediate inflammatory lung injury during ventilator-induced lung injury. C-Jun-NH2-terminal kinase was also involved in alveolo-capillary leakage and edema formation, whereas MMP8 inhibited alveolo-capillary protein leakage.

Introduction

Ventilator-associated lung injury arises as a clinical complication of mechanical ventilation. Its severe and advanced form, acute respiratory distress syndrome (ARDS), is associated with a high mortality and limited therapeutic options [1–3]. ARDS may contribute to multiple organ failure, a major cause of death in intensive care units [4]. Ventilated patients with otherwise healthy lungs seldom develop ventilator-associated lung injury while those with pulmonary inflammation are predisposed to such injury [5,6].

Animal models have been used extensively to model ventilator-induced lung injury (VILI) yet the underlying mechanisms remain incompletely understood. Recent research has focused on intracellular signaling pathways involved in the development of VILI, among which include the mitogen-activated protein kinase (MAPK) pathways, key regulators of inflammation [7–9]. MAPKs belong to an evolutionarily conserved and ubiquitous signal transduction superfamily of Ser/Thr protein kinases that regulate multiple cellular processes including apoptosis, growth, differentiation and responses to environmental stimuli. The MAPK superfamily includes three primary signaling cascades: the extracellular signal regulated kinases (ERK1/2), the c-Jun NH2-terminal kinases (JNK) and the p38 MAPKs. MAPK activation is associated with various forms of inflammatory lung injury. Therefore, strategies to modulate MAPK activation may have therapeutic benefit in this context [10,11].

The global gene expression profiling approach has provided new insights into the mechanism of VILI. The observed differential activation of genes involved in the coagulation cascade, extracellular matrix production and intercellular communication in the context of VILI, suggests that this disease represents a complex rather than purely inflammatory process, where cellular mechanotransduction plays a key role [5,12,13].
The goals of this study were three fold: First we investigated the role of the p38 MAPK/MAPK kinase-3 (MKK3) and JNK signaling pathways in VILI. We measured lung injury parameters in response to ventilation in C57/BL6 (wild-type) mice and strains genetically deficient in MKK3 and JNK1. Second, we have assessed global gene expression changes in our model using microarray-based gene expression profiling. We describe series of genes differentially regulated by ventilation in either wild-type or jnk1−/− mice, and thereby provide insight into potential mechanisms of resistance to VILI. Third, we identify a role for matrix metalloproteinase-8 (MMP9) in alveolo-capillary permeability independent of MAPK.

Materials and Methods

Experimental design

Adult C57/BL6 (wild-type) mice and mkk3, jnk1, mmp8 genetically deficient genotypes (−/−) were used for experiments (n = 192, weight = 20–30 g). Wild-type mice were purchased from Jackson Laboratory. Mkk3−/− and jnk1−/− mice were generated by R. Flavell (Yale University) and mmp8−/− mice were generated by S. Shapiro (University of Pittsburgh). All wild-type and genetically deficient mice used in this study were in the C57/BL6 background and matched for age and sex in all experiments. Mice were allowed to acclimate for 1 week with rodent chow and water ad libitum prior to the experiments. All animals were housed in accordance with guidelines from the American Association for Laboratory Animal Care. The Animal Care and Use Committee of the University of Pittsburgh approved the protocols. Mice were anesthetized with the intraperitoneal (i.p.) injection of a mixture of ketamine (150 mg/kg) and acepromazine (2.5 mg/kg) (Sigma-Aldrich Biochemical Co.). Tracheostomy was performed and a 20 G canula was inserted in the trachea. Groups of wild-type, mkk3−/− and jnk1−/− mice were randomized into 4 treatment conditions: control, 2-hour ventilation with 20 ml/kg tidal volume, 4-hour ventilation with 20 ml/kg tidal volume and 8-hour ventilation with 10 ml/kg tidal volume. Mice deficient in mmp8−/− were used for control and 8 hours mechanical ventilation conditions. Control animals were sacrificed immediately after anesthesia (n = 5–6 animals/group). The other animals were mechanically ventilated (n = 5–9 animals/group/condition). Mice were sacrificed 2 hours after anesthesia (n = 5–8 animals/group/condition). Mice were sacrificed immediately after anesthesia (n = 5–8 animals/group/condition). Mice were sacrificed 2 hours after anesthesia (n = 5–8 animals/group/condition). Mice were sacrificed 2 hours after anesthesia (n = 5–8 animals/group/condition). Mice were sacrificed 2 hours after anesthesia (n = 5–8 animals/group/condition).

Necropsy protocol, tissue and bronchoalveolar lavage fluid analysis

At the end of the experiment the abdomen and the chest of the animals was opened up. The left lung was isolated with surgical silk tied around the left main bronchus. The right lungs were lavaged using 0.5 ml saline (n = 5 animals/group/condition). The lavage volumes were inserted and withdrawn 3 times via the trachea canula to equalize volumes. 0.3–0.4 ml bronchoalveolar lavage fluid (BALF) was recovered per animal. One hundred microliter of BALF was mounted on glass slides by cytopsinning for 10 minutes at 1000 rpm (Cytospin 3, Shandon Scientific) and stained with hematoxin-lisin-eosin for differential cell count. Two hundred cells were counted per sample. The rest of the fluid was immediately centrifuged (2500 rpm for 10 minutes) at 4°C. The supernatant was stored at −20°C for cytokine analysis. The pellet was resuspended in 1 ml PBS for quantitative cell count. The cells were counted in a hemocytometer (Hauser Scientific). The right lung tissue was snap frozen and used for protein extraction. Subsequently, the ligation from the left main stem bronchus was removed and the lungs were used for histology. For microscopic morphology analysis, lungs were inflated with 0.5 ml of 2% paraformaldehyde through the tracheostomy canula for 1 minute then harvested (n = 5 animals/group). The lungs were fixed for 2 hours in 2% paraformaldehyde and submerged in 30% sucrose overnight. The following day, the tissue was snap frozen in liquid nitrogen and stored at −80°C. The frozen tissues were embedded and stained with hematoxin-lisin-eosin for histology or used for cell death analysis (TUNEL staining). An experienced pathologist analyzed the lungs in a double-blinded fashion.

Lung microvascular permeability analysis and wet-to-dry weight ratio measurement

Evans Blue (EB) dye extravasation to the lung interstitium was used to quantify permeability changes following mechanical ventilation. EB dye (20 mg/kg, Sigma-Aldrich) was injected into the jugular vein of ventilated and control animals (n = 3–5 animals/group/condition). Mice were sacrificed 2 hours after dye injection [14]. Following the right main stem bronchus was tied off including the surrounding vasculature. The heart was punctured and 0.5 ml blood was collected. Blood was centrifuged to obtain plasma. The lungs were perfused with 1 ml normal 0.9% saline via the beating right ventricle to remove the remaining blood from the pulmonary circulation. The right lungs were harvested, blotted dry on paper towel and used for wet-to-dry weight ratio measurement. The left lungs were used for permeability measurement. Left lungs were homogenized in 1 ml 0.9% normal saline. For EB dye extraction and permeability analysis we used the method described by Belperio et al [15] with minor modifications. In brief, lung homogenates were incubated with formamide for at 60°C for 12 hours and centrifuged at 2000 g for 30 minutes. EB dye in the plasma and in the lung tissue was quantified using a dual-wavelength spectrophotometer (620 nm and 740 nm). The following formula was used to correct for heine contamination at 620 nm absorbance (A):

\[
A_{620\text{corrected}} = A_{620\text{observed}} - (1.426 \times A_{720\text{observed}} + 0.03)
\]

We also used the universal turbidity correction factor for lung tissue described by Moitra et al [14]. We calculated the permeability index previously used by Belperio et al [15] to quantify EB dye extravasation to the lung parenchyma using the following formula: (lung tissue A_{620\text{corrected}}/g lung tissue)/plasma A_{620}.

Lung wet-to-dry weight ratios were measured to quantify pulmonary edema formation. Harvested right lungs were blotted dry on paper towel and their weights were measured. Following lungs were desiccated in 60°C-heated oven over 5 days period to obtain a stable dry weight [16]. Dried lung weights were measured and wet-to-dry ratio was calculated.

Blood pressure experiments

Tail vein mean blood pressure was continuously monitored for wild-type mice receiving 8 hours 10 ml/kg mechanical ventilation (n = 3 animals) using non-invasive blood pressure cuffs (Columbus NIBP-1, Columbus Instruments).
Cellular assays (ELISA, western blots)

The cytokine analysis of BALF for tumor necrosis factor-α (TNF-α) was carried out as described, using mouse specific kits (R&D Systems, Inc.) [17]. Total protein concentration was determined with the Coomassie Plus 200 Protein Assay (Pierce Biotechnology, Inc.). Western blot analysis was carried out as previously described for phosphorylated and dephosphorylated (total) forms of p38 MAPK and JNK [18,19]. We used p38 MAPK Kinase Assay Kit for phospho-p38 MAPK detection. Total p38 MAPK expression was assessed using rabbit anti-mouse polyclonal antibody (Cell Signaling Technology, Inc.). The phosphorylated and total forms of JNK MAPK were detected with rabbit anti-mouse polyclonal antibodies (Cell Signaling). We observed the expression of 3 forms of MMP8: pro-MMP8, active MMP8 and an inactive degradation product of MMP8 (85, 65 and 30 kDa molecular weight respectively) in lung tissue. MMP8 protein expression was previously described by Tester et al.[20]. We used rabbit anti-mouse polyclonal MMP8 antibody for detection (Santa Cruz Biotechnology, Inc.). GADD45α protein expression was assessed by Western immunoblotting using rabbit anti-mouse polyclonal antibody (Santa Cruz). GADD45α protein expression analysis was previously described by Fayolle et al [21]. β-actin expression was used as a loading control. Densities were quantified based on 3 individual samples per condition.

Microarray analysis

Total RNAs were extracted from lung tissues with Trizol (Invitrogen Corp.) [22]. Complementary RNAs labeled with the Cy5 fluorescent dye was generated and hybridized to CodeLink Uniset I 20K Bioarrays as recommended by the manufacturer (GE Healthcare Bio-Sciences Corp.) and previously reported by us [22]. All microarray data were normalized using the CyclicLoess normalization method (available at www.biocductor.com) to remove noise in the data [23]. For analysis we filtered out genes that did not pass manufacturer recommendation for quality control. The log2-transformed expression data were used in the downstream analyses. We analyzed the gene expression patterns of 3 controls and 4 ventilation-treated animals. For statistical analysis we applied Welch’s two-sample t-tests and non-parametric Threshold Number of Misclassification (TNoM) score from the Scoregene Package [available at http://compbio.cs.huji.ac.il/scoregenes] to find genes with significant expression changes. The p-values from the t-tests were adjusted for multiple testing using the false discovery rate (FDR) controlling procedure of Benjamini and Hochberg [24]. Genes which have the adjusted p-values less than 0.05, the TNoM scores equal to 0, and a fold-change in expression greater than 2 (on original data scale) were considered significantly changed [25]. This criterion for detecting differentially expressed genes is stringent, and can ensure the low false discovery rate. The color-coded heatmap was generated from significant genes using Java Treeview (available at www.sourceforge.net).

In order to find functional groups of genes over-represented in our dataset, we selected a bigger pool of differentially expressed genes using a less stringent criterion: p-values from t-tests (without FDR correction) less than 0.05, TNoM score equal to 0, and the fold-change in expression greater than 1.5 (on original data scale). The differentially expressed genes were analyzed using the GOstat program (available at www.gostat.wehi.edu.au), which identifies enriched functional groups of genes based on Gene-Onontology (GO) annotations. Gene groups with p-value<0.01 were considered overrepresented in our dataset (after FDR p-value<0.05 correction). The data discussed in this publication have been deposited in NCBI’s Gene Expression Omnibus (GEO, http://www.ncbi.nlm.nih.gov/geo/) and are accessible through GEO Series accession number GSE7742.

Real time TaqMan PCR

Quantitative RT-PCR was performed for 4 genes with increased expression following mechanical ventilation in wild-type and jnk−/− mice (n = 4 samples/condition). TaqMan PCR was executed as described previously [22]. Commercially available Assay-on-Demand primer probe sets (Applied Biosystems, Inc.) were used for Gadd45α (Mm00432802_m1), for Wisp2 (Mm01247817_m1) for Atf4 (Mm00515324_m1) and for Mmp8 (Mm00772335_m1). Gene expression was measured relative to an endogenous reference gene, mouse β-glucuronidase (Gusb Mm00446957_m1). The results were log2 base transformed and the arithmetical means of 4 measurements were compared.

Tissue immunohistochemical-staining and terminal transferase-mediated dUTP nick-end labeling assay

Lung tissues were fixed with 2% paraformaldehyde, merged in 30% sucrose overnight and snap frozen. Sections of lung were prepared and immunostaining was performed as described [26]. We used GADD45α rabbit polyclonal primary antibody (Chemicon International, Inc.) and goat polyclonal IgG primary antibody for MMP8 (Santa Cruz Biotechnology, Inc.). For terminal transferase-mediated dUTP nick-end labeling (TUNEL) assay FITC-Avidin D dye was used [27]. Results were quantified based on 4 individual samples/group.

Statistics

Results are presented mean±SEM. Kruskal-Wallis test was performed for multiple group comparison and intergroup differences were analyzed with Wilcoxon Rank Sum Test [28] with SPSS statistics software (SPSS, Inc.). Significance level was p<0.05. Microarray statistics and tools are detailed above.

Results

Mechanical ventilation induces lung injury in vivo

We ventilated C57/BL6 mice using moderate tidal volume ventilation (10 ml/kg, 8 hours) with low PEEP (2 cmH2O). This ventilation strategy allowed us to observe neutrophil influx into the lungs without significant animal mortality and resulted in substantial lung injury. For all animals, total cell count and total protein content were measured in the bronchoalveolar lavage fluid (BALF). Mechanical ventilation resulted in the increase of total cell count in the BALF (Figure 1A), and significant neutrophil recruitment to the alveoli (Figure 1B). We also observed increased protein content in the BALF following 8 hours mechanical ventilation (Figure 1C).

To maximize lung injury following mechanical ventilation mice were ventilated with high tidal volume (20 ml/kg) and low PEEP (2 cmH2O) for 2-4 hours. High tidal volume ventilation was used to induce rapid changes in cell count, alveolo-capillary permeability and MAPK activation. Total cell count in the BALF increased in a time-dependent fashion during the course of mechanical ventilation (20 ml/kg), (Figure 2A). Total protein level in the BALF was significantly higher as early as 2 hours of ventilation when compared to controls (Figure 2B). The levels of the pro-inflammatory cytokine tumor necrosis factor-alpha (TNF-α) were also analyzed in the BALF. TNF-α levels were increased after 2 hours of ventilation [data not shown], but were not detectable at later ventilation time (4-8 hours). The detailed description of qualitative cell count and total protein is shown in Table S1. Hematoxylin-eosin stained lung tissues were compared following
mechanical ventilation. Mechanical ventilation resulted in lung tissue injury marked by alveolar-septal thickening and neutrophil granulocyte infiltration to the parenchyma (Figure 3). Mean blood pressure was continuously monitored during mechanical ventilation and significant blood pressure drop was noticed only during the 8th hour (Table S2).

Mice deficient in MKK3 and JNK1 are less susceptible to ventilator-induced lung injury

We examined whether VILI affects the activation of JNK1 and p38 MAPK, members of major inflammatory signaling pathways involved in lung injury. The levels of phosphorylated JNK and p38 MAPK were increased following mechanical ventilation (20 ml/kg, 8 hours), as determined by Western immunoblot analyses of corresponding phospho- and dephospho- forms (Figure 4A and B). To further assess the role of p38 MAPK and JNK1 in VILI, we ventilated mice genetically deficient either in mkk3 (mkk3−/−), the major upstream activating kinase of p38 MAPK, or jnk1 (jnk1−/−), and compared their lung injury indices to that of wild-type mice. The mkk3−/− mice were used for study since p38 MAPK deficient
mice are embryonic lethal. In the absence of ventilation, no differences between the three strains were observed with respect to total cell count, protein, or TNF-α levels in the BALF. Mechanical ventilation (20 ml/kg, 4 hours) resulted in significantly higher total cell count in the BALF of wild-type mice relative to that of mkk3^{−/−} or jnk1^{−/−} mice (Figure 5A). TNF-α levels were significantly higher in wild-type animals than in mkk3^{−/−} and jnk1^{−/−} mice (Figure 5B). TNFα analysis was performed after 2 hours ventilation due to the early and transient nature of this response.

When neutrophil influx was quantified following ventilation (10 ml/kg, 8 hours), we found that both mkk3^{−/−} and jnk1^{−/−} mice exhibited reduced leukocyte infiltration when compared to wild-type mice (Figure 5C). Quantified TUNEL staining for cell death showed that wild-type mice have increased cell death when compared to mkk3^{−/−} and jnk1^{−/−} mice following volume ventilation (10 ml/kg, 8 hours). Values expressed as number of TUNEL staining cells/1000 cells. *represents significant differences between control and ventilated animals, † represents significant differences between wild-type and genetically deficient animals.

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wild-type mice (Figure 5C). Lung cell death was also assessed with TUNEL staining and we observed that wild-type mice showed significantly higher numbers of positively staining cells, compared to mkk3⁻/⁻ and jnk1⁻/⁻ mice (Figure 5D). To localize cellular death in the lung tissue we performed cell specific immunostaining. TUNEL staining was principally localized to the alveolar epithelium. Other cell stains using neutrophil granulocyte marker (Ly6), macrophage (Mac1) and endothelial cell-specific (CD31) markers did not reveal increased apoptosis in these cell types (data not shown).

Wild-type or mkk3⁻/⁻ mice responded to mechanical ventilation with significant increase of BALF protein levels relative to their corresponding non-ventilated controls. However, ventilation did not affect the protein levels in jnk1⁻/⁻ mice (Figure 6A). Subsequently, we assessed pulmonary edema and alveolo-capillary permeability changes in mechanically-ventilated mouse strains. Wet-to-dry lung weight ratios indicated increased lung water content in wild-type and mkk3⁻/⁻ mice, but not in jnk1⁻/⁻ mice which were resistant to pulmonary edema formation (Figure 6B). Analysis of Evans Blue dye extravasation revealed increased microvascular permeability in both wild-type and mkk3⁻/⁻ mice (Figure 6C). However no permeability changes were observed in jnk1⁻/⁻ mice following 4 hours mechanical ventilation (Figure 6C).

When total protein levels were assessed in the BALF at 8 hours we found that there was a modest increase in jnk1⁻/⁻ mice as well (Table S1). These findings further support the observation that mice lacking JNK1 or MKK3 are less susceptible to ventilator-induced inflammation and cell death. Additionally, we found that jnk1⁻/⁻ mice are also relatively resistant to pulmonary edema formation.

Differential expression of genes in VILI

To assess possible differences in gene expression patterns following mechanical ventilation, we used gene expression analysis by microarray. Since jnk1⁻/⁻ mice were the most resistant to VILI we also compared the gene expression profile of jnk1⁻/⁻ mice to wild-type mice in the absence or presence of ventilation. To identify groups of genes which are significantly overrepresented in our dataset, we used Gene Ontology (GO) analysis (t-test p-value<0.05, TNoM score = 0 and fold-change of expression >1.5, see “Materials and Methods” for details). Wild-type mice responded to mechanical ventilation with the significant enrichment (p<0.05) of upregulated genes in extracellular matrix, stress-response and inflammation-related functional groups (Figure 7A). In order to assess how jnk1⁻/⁻ mice differ from wild-type mice we analyzed gene expression patterns prior to and following mechanical ventilation. When control (wild-type and jnk1⁻/⁻) mice were compared in the absence of ventilation, jnk1⁻/⁻ mice showed the significant enrichment of upregulated genes in cytoskeleton, calcium ion binding and muscle contraction functional groups (Figure 7B). Mechanical ventilation in jnk1⁻/⁻ mice resulted in the significant enrichment of downregulated genes in immune system function, biopolymer metabolism and muscle contraction functional groups and the significant enrichment of upregulated genes in the acute phase response functional group (Figure 7C). These results strengthen our findings that jnk1⁻/⁻ mice respond to lung injury with an altered inflammatory response. Using more stringent statistical criteria (t-tests p-value<0.05 with FDR correction, TNoM score = 0 and fold-change of expression >2, see “Materials and Methods” for details) we identified 103 genes whose expression significantly changed following ventilation in wild-type and/or in jnk1⁻/⁻ mice. Expression of these genes is shown in a color-coded heatmap format in Figure 8A. Gene names with expression values are not shown.

Figure 6. Alveolar protein content, lung microvascular permeability, and wet-to-dry weight ratio measurement in wild-type, mkk3⁻/⁻ and jnk1⁻/⁻ mice. (A) Total protein levels were significantly increased in wild-type and mkk3⁻/⁻ mice following ventilation (20 ml/kg, 4 hours). No differences in total protein levels were observed in the jnk1⁻/⁻ mice. (B) Wild-type and mkk3⁻/⁻ mice responded to mechanical ventilation with pulmonary edema formation (20 ml/kg, 4 hours). Pulmonary edema formation was quantified by measuring the wet and desiccated dry weight of lung tissue. No significant lung water changes were detected in jnk1⁻/⁻ mice. (C) Increased microvascular permeability was detected with Evans Blue (EB) dye extravasation method in wild-type and mkk3⁻/⁻ mice following mechanical ventilation (20 ml/kg, 4 hours). Mice lacking jnk1 gene did not show increased permeability following mechanical ventilation. Changes in permeability are expressed as a ratio of lung tissue/blood plasma to correct for differences in volumes of injected dye to the circulation. *represents significant differences between control and ventilated animals, N.S. = non-significant change between control and ventilated mice.

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included in the online data supplement (Table S3). We confirmed the expression results of four differentially expressed genes (Figure 8B). Growth arrest and DNA-damage-inducible protein-45a (gadd45a), WNT1 inducible signaling pathway protein 2 (wisp2), activating transcription factor 4 (aft4) and matrix metalloproteinase-8 (mmp8) microarray expression findings corresponded with TaqMan RT-PCR results (Figure 8B).

We chose to further validate the expression of gadd45a and mmp8. The mmp8 gene was chosen because of its remarkable increase in expression following mechanical ventilation (Figure 8B). Gadd45a expression was increased following mechanical ventilation, and this increase was significantly higher in jnk1/2−/− mice when compared to wild-type mice (Figure 8B). Co-immunostaining was performed for GADD45a and MMP8 proteins in lung tissue from wild-type mice (Figure 9, A and B). Increased GADD45α staining was evident in ventilated wild-type mice relative to non-ventilated controls. Multiple cell types expressed GADD45α protein, which localized primarily in the cytoplasm. MMP8 expression was also increased following ventilation but it was restricted to certain cell types, presumably mononuclear cells, and localized primarily in the cell membrane (Figure 9, A and B). Immunoblot analysis showed increased protein expression of MMP8 (Figure 10A) and GADD45α (Figure 10B) following mechanical ventilation.

MMP8 regulates microvascular permeability in lung injury

To assess the physiological relevance of MMP8 in VILI, mmp8 gene deleted mice (mmp8−/−) were ventilated and their lung injury parameters were compared to wild-type mice. The mmp8−/− mice displayed increased total protein levels in the BALF following ventilation, relative to wild-type mice (Figure 11A). Increased Evans Blue dye extravasation was also detected in mmp8−/− mice when compared to wild-type mice (Figure 11B), whereas no differences in lung edema formation were observed (data not shown). However differences in total and differential cell count in the BALF were not detected between the two strains (Figure 11C and D).

Discussion

The role of mitogen-activated protein kinases in ventilator-induced lung injury

Although the pathology of VILI has attracted intensive clinical and experimental investigation, at present, the mechanisms of injury remain only partially explored [29]. MAPK are involved in transmitting various extracellular signals from the cell surface to the nuclei but have only recently been suggested as mediators of VILI [30]. Uhlig et al. described the increased activation of JNK, p38 and ERK MAPK following in vivo mechanical ventilation of rats for 1 hour. JNK and ERK1/2 activation were significantly larger when high-pressure ventilation (equal to 36 ml/kg tidal volume in their model) was used instead of low pressures (equal to 18 ml/kg tidal volume). p38 MAPK activation increased approximately 2 fold following 1-hour high pressure mechanical ventilation [30]. Increased activation of ERK1/2, JNK and p38 MAPK were also described by Li et al. in a mouse model of VILI [31]. In our setting we also detected increased JNK and p38 MAPK activation following mechanical ventilation. We were interested to explore how mice respond to mechanical ventilation in the absence of major MAPK signaling pathways. Mkk3−/− and jnk1−/− mice that were subjected to the same ventilation regimen as their wild-type counterparts were more resistant to VILI. Li et al. also reported altered neutrophil sequestration in the lung tissue when jnk1−/− and jnk2−/− mice were ventilated with high tidal

Figure 7. Gene Ontology analysis. Gene expression ratios were analyzed under the following conditions: (A) wild-type mouse ventilation versus control (total genes: 335), (B) jnk1−/− mouse control versus wild-type mouse control (total genes: 314), and (C) jnk1−/− mouse ventilation versus control (total genes: 686). Values represent gene numbers enriched in a functional annotation. Functional groups of upregulated genes are shown on the right side of the panel and groups of downregulated genes are shown on the left side of the panel. Gene symbols and names: amphiregulin (Areg), matrix metalloproteinase-8 and 9 (Mmp8, Mmp9), toll-like receptor 6 (Tlr6), p-selectin (Selp), interleukin 17C (Il17c), chemokine ligand 2 (Ccl2), interleukin 6 and 1b (Il6, Il1b), serine protease 3 (serpina3), serum amyloid A3 (Saa3), signal transducer and activator of transcription 3 (Stat3), calgranulin A (S100a8), chemokine ligand 20 (Ccl20), IgG Fc receptor (Fcgri3), myosin-light chain (Myf5), alpha1 actin (Acta1), troponin C (Tnnc2), calmodulin (Calm), atpase 2A1 (Atp2a1), casequestrin 1 (Casq1), transglutaminase 3 (Tgm3), lystate hydroxylase 1 (Plod1), small proline-rich protein 2a (Spr2a), t-box 6 (Tbx6), troponin i2 (Tnni2), alpha3 actin (Acta3), interleukin 1 (il1), monocyte chemoattractant protein 2 (Cc2), chemoreceptor 13 (Ccr13), eg. matrix metalloproteinase 11 (Mmp11), kruppel-like factor 2 (Klf2), alpha actin (Acta), troponin i2 (Tnni2), small muscle protein (Smox), orosomucoid (Orm).

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It is important to point out that in our model significant neutrophil influx was only detected after 8 hours, which may be a result of the lower tidal volumes used in this study. In addition to inflammation, we observed increased alveolar protein accumulation, lung microvascular permeability and pulmonary edema formation in our model of VILI that suggests increased alveolo-capillary barrier permeability. Double-isotope imaging studies of ventilated rats performed by de Prost et al. showed that mechanical ventilation with pressures greater than 20 cmH₂O, (corresponding to 13.7±4.69 ml/kg tidal volume in their setting) results in permeability changes in both alveolar and capillary membranes [32]. In our model, pulmonary edema formation preceded neutrophil granulocyte infiltration to lung parenchyma during mechanical ventilation, suggesting that permeability changes can also take place without significant inflammation. Previously Quinn et al. reported similar findings in a rat model of VILI [33]. We observed only moderate blood pressure drop in our animals following 7 hours of mechanical ventilation and therefore cardiogenic edema formation is unlikely to be the reason for the early increase in lung water content. Our

Figure 8. Differential gene expression change following mechanical ventilation in wild-type and jnk1⁻/⁻ mice. (A) The pattern of 103 differentially expressed genes is displayed. The gene expression profile of controls and animals subjected to mechanical ventilation (10 ml/kg, 8 hours) is compared. Confirmed genes: growth arrest and DNA-damage-inducible protein-45alpha (gadd45a), WNT1 inducible signaling pathway protein 2 (wisp2), activating transcription factor 4 (atf4) and mmp8 are highlighted. red = upregulation, blue = downregulation, yellow = null expression. Big columns represent wild-type control, wild-type ventilated, jnk1⁻/⁻ control and jnk1⁻/⁻ ventilated mice. Small columns show the gene expression profile of one animal. Each row represents one gene. Gene symbols are shown on right side of the panel. For complete gene names please refer to Table S3. (B) Microarray and confirmatory TaqMan RT-PCR expression profile of gadd45a, wisp2, atf4 and mmp8 genes. The increased expression gadd45a following ventilation was identified by microarray and verified with RT-PCR. Jnk1⁻/⁻ mice had a higher expression of gadd45a after ventilation than wild-type mice. Wisp2 expression was decreased in both wild-type and jnk1⁻/⁻ mice following mechanical ventilation. RT-PCR confirmed the microarray findings. Microarray results showed that atf4 gene was regulated only in jnk1⁻/⁻ mice and RT-PCR verified this finding. Mmp8 showed increased expression with ventilation on microarray and with RT-PCR verification, which was similar in both wild-type and jnk1⁻/⁻ mice. *represents significant differences between control and ventilated animals, †represents significant difference between wild-type ventilated and jnk1⁻/⁻ ventilated mice.

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results show that mechanical ventilation resulted in increased alveolo-capillary permeability and subsequent pulmonary edema formation in mkk3<sup>−/−</sup> mice, whereas jnk1<sup>−/−</sup> mice were relatively resistant to alveolar fluid accumulation when compared to wild-type mice. Petrache <i>et al.</i> demonstrated that cultured human pulmonary endothelial cells respond to TNF-α stimulation with microtubule destabilization and subsequent barrier dysfunction [34]. The lack of TNF-α response could, at least partially, account for delayed increase in lavage protein levels in jnk1<sup>−/−</sup> mice. Another possible explanation for relative resistance to alveolar protein-rich fluid accumulation is reduced epithelial apoptosis in jnk1<sup>−/−</sup> mice. Increased apoptosis was described in animal models of VILI [35] and in human ARDS [36]. Multiple cell types were shown to undergo apoptosis in response to acute lung injury including alveolar epithelial cells, endothelial cells and polymorphonuclear granulocytes [37–39]. In our model TUNEL staining displayed an epithelial localization. Given the moderate tidal volume mechanical ventilation we argue that the observed cell death is not severe and it is due to apoptosis rather than epithelial cell necrosis. JNK MAPK pathways are involved in pro-apoptotic signaling and p38 MAPK isotypes can be pro- or anti-apoptotic [40,41]. A reduced cell death response was observed in both mkk3<sup>−/−</sup> and jnk1<sup>−/−</sup> mice, but the reason why only jnk1<sup>−/−</sup> mice showed reduced alveolo-capillary permeability remains to be investigated. Recently Li <i>et al.</i> also showed decreased edema formation and apoptosis in ventilated jnk1<sup>−/−</sup> mice when compared to their wild-type counterparts [42].

In our model both high and moderate tidal volume ventilation strategies with low PEEP resulted in lung injury. Previously Tremblay <i>et al.</i> [17] and Belperio <i>et al.</i> [15] showed that moderate tidal volume ventilation with low PEEP increases proinflammatory cytokine and neutrophil sequestration in rodent lungs. Our results show that extended moderate tidal volume ventilation with low PEEP can induce injury comparable to higher tidal volumes.

**Mechanisms of ventilator-induced lung injury**

A further aim of our experiments was to assess mechanisms of VILI. Expression changes of inflammation (eg., Il6, Il1b), stress response (eg., Thi6, Selp) and extracellular matrix-related genes (eg., Areg, Mmp9) dominated in wild-type mice following 8 hours ventilation (Figure 7A). Similar gene expression patterns have been previously described by our laboratory and others [5,13,43], and may have a central role in pathogenesis of VILI [15,44,45]. In this study we identified Mmp8 (neutrophil collagenase), an extracellular matrix-related protein, previously unknown to be involved in VILI. Winkler <i>et al.</i> found elevated Mmp8 levels in endotracheal aspirate of children with respiratory distress [46]. Owen <i>et al.</i> described that the membrane-bound form of this enzyme regulates neutrophil migration in lung tissue [47]. In their model, mmp8<sup>−/−</sup> mice displayed increased inflammation 24 hours following LPS injection. Tester <i>et al.</i> have recently shown that mmp8<sup>−/−</sup> mice have an impaired initial response to LPS challenge, but once
neutrophil infiltration takes place in the lung, the effect is sustained [20]. We observed increased MMP8 gene and protein expression following mechanical ventilation in wild-type mice. MMP8 was localized primarily on the cell surface of mononuclear cells as previously suggested [20].

Mmp8−/− mice responded to lung injury with increased microvascular permeability and alveolar protein accumulation relative to wild-type mice suggesting increased alveolo-capillary permeability to protein. However differences in neutrophil infiltration and pulmonary edema were not seen (Figure 11). In a model of wound healing Gutierrez-Fernandez et al. found that mmp8−/− mice have delayed neutrophil granulocyte apoptosis [48]. They speculated that extended neutrophil presence enhances local damage. In our context the delayed presence of inflammatory cells could lead to alveolar injury and subsequent permeability changes. In the same model the authors describe that MMP8 forms complexes with MMP9. In the absence of MMP8, increased MMP9 production was detected. Elevated MMP9 levels lead to increased vascular permeability in a model of hyperoxia and endotoxin-induced lung injury [49]. The effect of increased MMP8 expression in our model is detailed in Figure 12. This new observation sheds light on a previously unknown mechanism in VILI, which warrants further investigation.

Jnk1−/− mice were relatively resistant to VILI, and their global gene expression patterns differed from that of wild-type mice.
Besides their gray color (versus black for wild type and mkk3−/− mice), jnk1−/− mice do not differ phenotypically from their wild-type counterparts. We speculated that analysis of the gene expression profile in jnk1−/− mice would provide information on their resistance to injury. The jnk1−/− mice responded to ventilation with the downregulation of genes significantly over-represented in the immune response system (e.g., Ccl8, Il1) and biopolymer metabolic processes (e.g., Mmp11) functional groups. A small number of genes enriched in acute phase response functional group were upregulated (e.g., Stat3). We did not observe a significant expression change of groups of inflammatory genes in jnk1−/− mice, which was prominent in ventilated wild-type mice (Figure 7A and C).

Jnk1−/− animals also displayed significant baseline overexpression of cytoskeleton genes and many were significantly enriched in the muscle contraction functional group (Figure 7B and C, Table S3). Cytoskeletal reorganization upon cyclic stretch has been demonstrated in pulmonary arterial endothelial cells [38]. Birukov et al. showed that cytoskeletal rearrangement depends on the magnitude of cell stretch. Other studies suggest that JNK inhibition attenuates actin cytoskeleton remodeling [50]. Our gene expression analysis confirms previous observations that JNK is involved both in the mechanotransductive and an inflammatory mechanism of VILI [31,42,51].

Increased alveolar epithelial cellular apoptosis has been noted following moderate tidal volume ventilation [52]. JNK signaling is pro-apoptotic and thus jnk1−/− mice are resistant to various pro-apoptotic stimuli [40]. We show that GADD45α expression in response to ventilation was further enhanced in the absence of JNK1. GADD45α has previously been identified as a candidate gene in VILI [5,43]. GADD45α have been shown to regulate JNK and p38 MAPK signaling to promote apoptosis [53]. However others suggest that JNK activation can precede or occur independently of GADD45α activation [54]. At present, we can only speculate that JNK modulates GADD45α activation directly (Figure 12) or that the effect is mediated via nuclear-factor κB, a major regulator of both JNK and GADD45α [41].

We conclude that MAPK (including MKK3/p38 MAPK and JNK pathways) play a central role in coordinating various forms of injury displayed in VILI. MAPK are involved in transmitting signals of cellular inflammation, mechanotransduction, and apoptosis. A separate mechanism that involves MMP8 is responsible at least in part for increased alveolo-capillary protein permeability in VILI. Our results suggest that strategies to modulate MAPK and/or MMP8 activation may have potential therapeutic benefit in patients suffering from ventilator-associated lung injury/ARDS.

### Supporting Information

**Table S1** Indices of lung injury in bronchoalveolar lavage fluid.

<table>
<thead>
<tr>
<th>wt</th>
<th>mkk3−/−</th>
<th>jnk1−/−</th>
</tr>
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<tbody>
<tr>
<td><em>n</em></td>
<td>5–8</td>
<td><em>n</em> = 5–8</td>
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Found at: doi:10.1371/journal.pone.0001601.s001 (0.68 MB TIF)

**Table S2** Mean blood pressure during 8 hours mechanical ventilation in wild-type mice. a = significant change 0th versus 6th hour ventilation, *p* < 0.05, *n* = 3/group, abbreviation: BP = blood pressure.

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### References


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### Author Contributions

Conceived and designed the experiments: AC TD. Performed the experiments: WW TD EI AH. Analyzed the data: NK WW TD AH. Contributed reagents/materials/analysis tools: SW NK WW AK MS. Wrote the paper: WW AC TD SR.


